General Tesla coil plans

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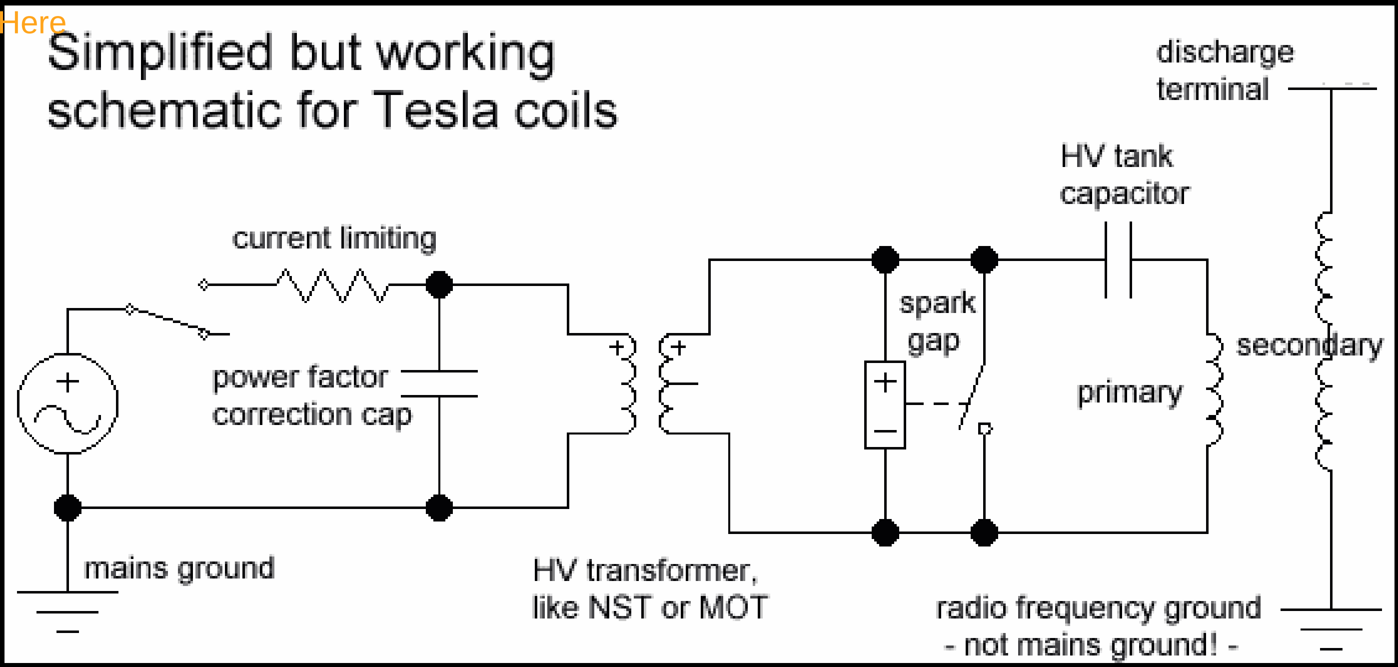

are the bare bones plans for making a Tesla coil.
Note that many absolutely essential safety factor parts are not shown, for simplicity of the schematic.

Some notes on design and other things:

and always bear in mind that the information here is not necessarily correct, and I only *assume* it to be correct to my best belief.

1) Current limiting

is only necessary for other transformers than neon sign transformers or transformers that do not have internal current limiting. A PFC capacitor on the mains side can act as "current limiting" to some extent. Otherwise, use resistive or additional inductive ballast (a MOT in series with shorted secondary winding).

2) Power factor correction - PFC

Power factor correction (PFC) shifts the VA rating of the transformer closer to actual input and/or output watts, and reduces input current needed. Reduced current is a benefit as all your switches, relais', fuse boxes and so on can be smaller - without PFC they would have to stand twice or more the current. Additionally, I^2*R losses in the wire resistances would be at least four times as high.

So, you might want to minimize current draw...

For example a 400VA cos(phi)=0.55 transformer takes in about 0.55*400VA ~= 200W with and without a PFC, but without a PFC it will draw about 2A from a 200VAC line. With an exactly matching PFC the input current is just ~ 1A. The capacitors are non polar capacitors, and it seems like they are mostly oil filled wax-paper capacitors used with mains voltage motors.

Method: First calculate transformer input impedance according to the values written on the transformer. For example 2.2A @ 220V gives Z = 220V/2.2A = 100 Ohm. Then calculate the PFC with C = 1/(wZ).
At 50Hz, this would be 1/(2*pi* 50 Hz * 100 Ohm) = 1/(pi*10) * 10^-3 F ~= 31 uF. You could also ask neon sign manufacturers if they have PFC caps for your particular transformer.

Note: A fellow coiler pointed out that the above calculated 100% PFC may generally not give the optimum value for spark-gap coils, as the gap break rate and other things change the power factor. For a nice match it might be easier to try out different capacitances, or calculate by simulation.

3) Grounding:

The only things that should/must be grounded to the mains grounding is the stuff on the mains side that you are going to touch (switches, dials, variac and so on).

The HV secondary side of the transformer must not be grounded at all, even if it is a center-tapped NST. Connecting together RF ground and any part of the HV primary, like done in some schematics, *is absolutely lethal*.

If you connected together the RF ground and some part of the HV primary circuit, you're a definite goner (=dead) should you come into contact with the secondary streamers (which can be lethal in any case, see 6 Skin effect).
The primary circuits capacitor energy would then flow partly (but partly is already enough) through your body towards the ground. Your pitiful 500..1000kOhm low-voltage body resistance is next to no obstacle for the high voltages - at 8kV, there could be potentially ~10 amps flowing through you, whereas even 5mA is enough to kill.

The Tesla coil secondary RF ground must be an own ground separate from mains ground. Reasons:

- this separate ground will sink RF current and voltage, which - if you used mains ground - would fry all equipment in your house, even the surge protectors.
- also, the mains ground wire is way too thin, and would have a considerable impedance at the high frequencies present. High impedance is not nice, as the TC base wouldn't be properly grounded then, and the wire would have a voltage drop from some 10s of kV on the base to 0V somewhere along the wire - i.e. the thin wire could still have a few kV some meters away from the coil base (corona, electrocution, damaged equipment etc).
- the other thing that is bad about a high impedance ground is that the zero voltage node will shift down along the wire to the place where the solid ground is. This will cause a phase shift also in the TC secondary, meaning you could get breakouts from any part along the coil, not just the top.

4) HV capacitor:

this has to be a HV pulse capacitor, able to give 100s of amps of current into a virtual short circuit and able to withstanding the forces resulting from this.

Additionally the capacitor should have minimal losses at radio frequency band - otherwise it will heat up and pop. Glass for example has huge losses at RF. That's why beer bottle (also called salt water) capacitors are not recommended.

Cap values generally range from 1nF to 50nF.

The current trend is moving away from "self rolled" capacitors and beer bottle caps. Now one generally makes big HV pulse capacitors from an array built of generally available, "low" voltage and low cost capacitors. Non-electrolytic flash unit capacitors (Panasonic for one) seem to be good. Small radio frequency rated pulse capacitors are the definite ones to use.

You wire them up as an array: make a string of capacitors in series in such a manner that the summed up total voltage rating of the string is larger than the input voltage (t.ex. 20kVDC strings used in a HV cap for a 8kVAC NST). Then, connect so many strings in parallel (ends together) that you end up with the desired capacitance.

Example: you want a 10nF cap and have a 8kVAC NST. NST will give SQRT(2)*8kVAC=12kV peak, and you need a bit larger than that, say 20kV strength. If you bought some pieces of 10 nF caps, rated 1kVDC, you'll first connect 20 in series. That is, hook them up in a string. The wires should be kept as short as possible. The total capacitance of *one* string is then C_{string} = 10 nanoFarad / 20 = 0.5 nanoFarad, and the total voltage rating $V_{max,string} = 20 * V_{max, one capacitor}$ = 20kVDC, as wanted.

Now, to get the full desired capacitance of 10nF, you have to hook a number of those

strings up in parallel. One string was 0.5 nanoFarad, so you would need 10nF/0.5nF = 20 strings in parallel.
In total, you will need 20 strings times 20 caps/string = 400 caps. That is pretty many, so you need to find a place that sells these small pulse caps cheap, for < $1 per piece.
But, the final MMC tank capacitor will be at least half cheaper than commercial HV pulse capacitors, and nevertheless performance wise very close to those commercial ones.

You should always have at least 5 strings in parallel (increase string length if necessary), because each string has to deliver huge currents. If you have multiple strings in series, each string will have to contribute less current and it will last longer than if you have just one string (which would blast in an instant.).

Together with the primary coil, the resonant frequency of this L-C circuit should be in the range 100kHz to 1MHz. Lower freq (~= less heat losses) is better for high power output and bigger diameter coils.

Resonant charging: the HV cap can be charged efficiently to higher voltages (if it endures them), by charging it in resonance to the transformer, at line frequency. The drawback is that this will increase stress on the transformer. And, the extra voltage is not "free", so it needs several AC frequency cycles before the capacitor reaches the (over-) voltage and makes the spark gap fire. Anyway, see 7) Resonance.

Please remember(!): 1) a HV capacitor will be lethal if you touch it. 2) HV caps can sometimes regain (lethal) charge if they stand around unused for a while and are not shorted out by connecting a wire between terminals. 3) a HV capacitor charged up using a 100kW transformer at 15kV is exactly as lethal as when it was charged with a tiny 50mW handheld flyback or ignition coil at 15kV (same amount of energy stored in all cases).

5) Filters:

all filters are missing in the schematic. You should install mains RF filters and, if possible, high voltage radio frequency RC-style low pass filters between spark gap and transformer. Choke filters are not recommended. They can cause additional voltage spikes. And insulation is also a problem if the chokes are too tight wound and too small - high voltage will jump over the choke then.

6) Skin effect:

Streamers are not harmless! Don't trust what you read about skin effect on some other sites!

High frequency current tends to flow closer to the surface of conductors, i.e. at very high frequencies a huge round 1m^2 area conductor will have current flow only on the surface - you could make the center hollow as the metal inside it conducts no current at all and only adds weight to the conductor.

Skin depth = depth at which current density is 1/e ~= 37% of maximum. There IS current flow at deeper than skin depth, even at four or five times skin depth, but it decreases fast.

You can calculate the skin depth with:

depth = 1 / SQRT (pi * freq * permeability * material conductivity)

Where:
material conductivity = 1 / material resistivity
*permeability = 4*pi*10^-7 * conductor relative permeability freq = frequency of signal fed through the conductor*

Use SI units! That's metric... Not webers, or inches, or anything more complicated.

Demo: with copper conductor and 800kHz. Copper has relative permeab. (to vacuum) of ~1, so permeability is vacuum permeability. Resistivity is 1.72*10^-6 ohm meter. Skin depth is thus 0.233 millimeters.

So, for good performance and only small losses in the HV primary circuit you don't need thick wire but a large surface area, like flat strips from alu foil, copper foil, etc for the NST filter->spark gap->cap->primary connectors.

The other thing is that skin effect applies not only to metals, but also includes blood vessels!

The streamers from the secondary are *dangerous to even lethal*, because the RF frequency lies outside the nerve cells detection ability which means that you don't notice that there are 100W of power travelling along your tissue and blood vessels, cooking you from inside out. Never do a stunt and touch or get close to the streamers! Instead, use long plastic rods with an end metal terminal that is connected to ground. With this, you can safely draw arcs off the coil.

7) Resonance:

the goal in a TC is to make both the primary high voltage side L-C-circuit and the secondary coil $L\text{-}C_{self\text{-}capacitance}$ - circuit resonant at the same frequency. In this way you get maximum power transfer from the primary tank cap to the secondary self capacitance. The secondary is series resonant, meaning low impedance and with high voltage accross components.

The resonant frequency can be calculated with

freq(res) = 1 / [2pi * square_root(L*C)].

In theory, the energy after the transfer from the tank capacitor to the secondary Cself remains about the same (W = 1/2 * C * U^2), but because the Cself is 1000 times smaller than the tank capacitor, the voltage accross the secondary is much higher.

Long streamers are generated by high voltage and high power, but also by growth of new streamers from the ends of previous ionized streamer channels - making it desireable to have the spark gap fire very fast.

The tank capacitor can be charged to higher voltage (resulting in more energy stored, according to power of ^2), taken the cap can stand the voltage. Raising the voltage is easiest done with resonant charging, where the impedance of the tank capacitor at line frequency matches the output impedance of the transformer.

For a 400VA 8kV 50mA transformer (Z=U/I=160 kOhm) at a mains frequency of 50 Hz such a tank cap would be near C=1/(wZ) = 1/(2*pi*50 Hz * 160 kOhm) = 20 nF. Note that resonant charging drops the transformer impedance, i.e. also the impedance seen from / reflected to the mains side.

The TC secondary acts similar like a 1/4 wave length resonator with standing waves. You'll have a constant zero voltage node at the grounded coil base and the first (low-high oscillating) maximum at the coil top. The secondary is roughly an inductance, so voltage leads 90 degrees to current, meaning at the coil base you have a (low-high oscillating) current maximum and at the top a constant current minimum.

There are of course also other wave modes, with more voltage maximums along the coil. If you put a large round plate through those parts of the coil, you'll get a multi-breakout-point coil, with streamers not just from the top capacitor. The problem is that you then have to eliminate strikes from the lowest inserted plate to the primary coil (if not, you would get constant white ground strikes...).

You can also build a 1/2 wave length resonator or twin coil - ground the middle of the coil, move the primary inductance to the coil middle, and add discharge terminals to both ends of the coil. Both ends will then have opposite voltage at any time. You can also split the coil and the primary inductance in two halves and move them apart.

7) Strike rail:

This one is absolutely necessary.
[Well, not really..., if you consider that the energy from a strike is less than was pumped into it, meaning that the voltage over the primary cap can not rise above supply voltage when a streamer hit occurs. OTOH I personally don't trust this to protect the cap, NST, and other equipment, so I always have a strike rail.]
The rail protects your primary circuit and transformer from direct hits from the secondary. The strike rail is an open (not closed!) loop of thick, non-insulated tubing or thread that is placed 1-2" above the outer ends of your primary coil. The rail is grounded to RF ground. It will intercept any streamers should they try to strike your primary coil and try to fry you at the control board, all mains equipment, the tank cap and everything else.

8) Notes on tuning:

tuning goes best with a sine wave signal generator (some mV or V) and a scope or spectrum analyzer connected to a small antenna. First determine the secondary resonant freq by feeding a sine signal to the secondary (with topload on), varying the frequency, and checking at which frequency you'll get the biggest spike on your spectrum analyzer or the highest amplitude on your scope. Then put the secondary in place, short out the spark gap and unconnect the transformer, and feed the same sine signal to the primary HV circuit. Adjust the tapping of the primary coil and possibly the height of your secondary until you see two maximum big spikes to the left and right of the secondary self resonant freq on your spectrum analyzer, but no peak at that self res.freq. Once that's done, your coil is optimally tuned.
